RESEARCH ON THE GREEN INNOVATION EFFECTS OF INFORMATION INFRASTRUCTURE CONSTRUCTION: TOWARDS A LOW-CARBON DEVELOPMENT IN CHINA

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Abstract. As new digital infrastructure propels the development of the digital economy, its role in driving green innovation amidst mandatory low-carbon development requirements warrants in-depth investigation. Leveraging urban information infrastructure data and Chinese listed firm data, this study examines how information infrastructure (II) advances green technological innovation (GTI) under carbon constraints. II boosts corporate GTI by 13.52% (quantity) and 11.88% (quality) while helping enterprises meet low-carbon requirements. Robustness tests such as the placebo test, PSM-DID test, instrumental variables test, and exclusion of particular samples test, confirmed the same findings. Further, the mechanism analysis showed that the II promotes the GTI of enterprises through accelerating corporate digital transformation for energy-performance alignment and easing green financing constraints for eco-innovation investments. The effect is affected by carbon-reduction pressure and enterprise life cycle heterogeneity. This study provides evidence for synergizing digital infrastructure with carbon governance, suggesting II deployment as a strategic lever for achieving dual innovation-carbon goals.
Keywords: *Broadband China strategy, green financing constraints, innovation quantity, innovation quality, low-carbon development*
JEL code: *O31 O32*

Introduction

Since the Industrial Revolution, human society has developed different development concepts at different stages. In the realm of climate change and environmental issues, green development has gradually become a new consensus for sustainable growth under binding low-carbon constraints (Dabbous and Tarhini, 2021). The report of Digital China Development (2021) released by the Cyberspace Administration of China pointed out that by the end of 2021, China had built 1.425 million 5G base stations, accounting for more than 60% of the world's 5G base stations (https://www.cac.gov.cn/2022-08/02/c_1661066515613920.htm). China has built the world's technologically most advanced information infrastructure. Against the backdrop of mandatory low-carbon development, this raises a critical inquiry: Can II (information infrastructure) construction, as the core enabler of the digital economy, empower corporate green development? This provides a novel lens to examine green development through the digital economy perspective. From the micro level, the critical factor in determining the green development of enterprises is to improve the green technology innovation ability of enterprises. With the deep integration of the digital economy and digital technology, the link between the enterprises' green technology innovation adoption ability and the development of the regional digital economy is increasingly close. On the one hand, from 2017 to 2021, China's data production increased from 2.3ZB to 6.6ZB, accounting for 9.9% of global data production in 2021, ranking second in the world (the data is derived

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from The Digital China Development Report, 2021). Under carbon neutrality constraints, data as a new production factor integrated into the production function offers a transformative pathway for GTI (green technological innovation)-enabled low-carbon transition. This unique factor of production provides a new feasible path for green technology innovation. On the other hand, the booming digital economy can catalyze a comprehensive green revolution spanning production factors, productivity, and production relations, achieving full-chain empowerment of GTI through digital decarbonization mechanisms (Hao et al., 2023). Aligned with low-carbon imperatives, this study examines the green innovation effects of information infrastructure construction within the digital economy framework.

The contribution of this paper is: First, unlike existing studies that focus on the green development effects of smart city (Wang et al., 2021), environmental regulation (Yu et al., 2023) and inclusive finance (Hong et al., 2022), we pioneer a carbon-constrained framework to empirically examine the relationship between II and GTI using the Broadband China strategy pilot as a quasi-natural experiment. Considering the complexity and diversity of information infrastructure construction, this article further measures the level of information infrastructure construction through per capita broadband access and per capita telecommunications income, Secondly, this article further enriches the innovation driven effects brought by information infrastructure from the perspectives of quantity and quality. This article integrates information infrastructure construction and enterprise green technology innovation into a unified framework, paying more attention to the dual improvement effect of the quantity and quality of innovation generated by information infrastructure construction. At the same time, it deeply explores the internal mechanism of this influence, which is conducive to a systematic and comprehensive understanding of the relationship between information infrastructure construction and enterprise green technology innovation. Thirdly, this article further elaborates on the differences in green technology innovation effects brought about by information infrastructure from the perspective of regional and enterprise life cycle.

The remaining study is structured below. The literature review is elaborated in section two, which integrates the theoretical framework with hypotheses. The study's hypotheses are also explained in this section. The third section presents the research methodology. The results are discussed in section four. Section fifth offers the study's conclusion with potential policy recommendations. The limitations of the study are also mentioned in this section.

Literature review

Under the background of the digital economy, relevant research on II construction and enterprise GTI is mainly explored from two aspects: economic effects brought by II and influencing factors of GTI. Therefore, this paper will elaborate on related literature from the above two aspects.

First, different from traditional infrastructure such as roads and railways, II is closely integrated with the digital economy and has become the core force for promoting technological and industrial reform. Existing studies are mainly conducted on the aspects of total factor productivity (Yu, 2022), labor employment (Zuo, 2021), enterprise transformation and upgrading (Li et al., 2019), environmental pollution (Wu et al., 2022), etc., in an attempt to explain the contribution of II construction to high-quality economic development. In addition, by virtue of the policy impact of Broadband China, Feng et al. (2023) studied the impact of II construction on urban innovation at the city level and found that the strategic pilot policy of Broadband China promoted innovation agglomeration and structure optimization, thus significantly improving the level of urban innovation. Yang et al. (2022) further verified this at the enterprise level.

Second, according to the definition of the United Nations Environment Programme, green technology, different from clean energy production technology and sustainable development technology, refers to the systematic technology system that can achieve economic, ecological, and social sustainable development. Braun et al. (1994) first summarized and proposed that green technology is a systematic technology that can improve the environment. It is a high-standard technology that emphasizes ecological improvement and a general term for products conducive to socially sustainable development. GTI can not only improve the total factor productivity of enterprises and increase corporate profits, but also help reduce environmental pressure and promote the green development of the whole society (Du et al., 2019). Existing studies mainly focus on the impact of financial policies (Flammer, 2021), environmental policies (Wang et al., 2022), and industrial policies (Carrión-Flores et al., 2013) on enterprises' GTI.

Further, under the background of the rapid development of the digital economy, more and more research has begun to pay attention to exploring the impact of digital infrastructure on GTI. In this regard, Ma and Wu (2022) studied the effect of smart city on the GTI. Zeng et al. (2023) further explored and found that the construction of intelligent cities promotes GTI through the increase of investment in science and technology and human capital level. Luo et al. (2023) find that network construction has become an essential driving force to promote urban green development from the city level. Different from the above studies, this paper attempts to study the impact of II construction on enterprises' GTI with the help of the policy impact of Broadband China. On the whole, existing studies have explored the green development effect brought by the digital infrastructure represented by the construction of a smart city. Still, there are few studies explicitly discussing the internal relationship between the construction of II and green development. Meanwhile, different from the existing studies using city-level data, this paper uses micro-enterprise data to refine the research topic. The influence mechanism and heterogeneity of II construction on enterprises' GTI are also analyzed from the perspectives of innovation quantity and innovation quality.

Theoretical mechanism and research hypothesis

According to the theory of environmental adaptation, enterprises adapt themselves to the policy environment and achieve sustainable development. At present, environmental regulation and low carbon targets have become the most crucial external policy environment to promote enterprises' GTI. Since the 18th CPC National Congress, the construction of Internet infrastructure has entered a fast lane, providing practical support for the development of the digital economy. The popularization of II has promoted the formation of new economic forms such as big data, platform enterprises, and blockchain, which has triggered comprehensive changes in economic structure, development mode, and development goals, and the comprehensive empowerment of green development has gradually emerged (Shao et al., 2016; Shahzad et al., 2022). According to the existing literature, enterprise GTI is generally further divided into two dimensions: innovation quantity and innovation quality. This paper believes that just as infrastructure networks such as high-speed rail provide information, intelligence, and capital for enterprise innovation, II construction is essential, malleable, and intelligent. It provides primary conditions, expansion channels, and innovation resources for enterprises to carry out GTI.

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Therefore, II construction can not only promote the magnitude change of enterprises' GTI but also lay a foundation for the breakthrough development of enterprises' GTI, that is, promote the improvement of the quality of enterprises' GTI.

Digital transformation mechanism

Different from traditional technical facilities, II is the carrier of the digital economy and digital technology, which can significantly promote the digital transformation of enterprises. On the one hand, II can provide the underlying support for the digital transformation of enterprises through the improvement of broadband user scale (Alessia and Ludovico, 2022; Hu et al., 2023). On the other hand, the construction of II drives the accumulation of human capital by accelerating the accumulation of talents, thus promoting the digital transformation of enterprises. The green development effect of digital transformation has also been verified. With the improvement of enterprises' digitalization level, enterprises' ability to identify and obtain information has been dramatically improved, and cutting-edge, high-tech, and high-conversion information will be absorbed and used for reference. After integration, enterprises' innovation vitality will be greatly stimulated, and green innovation ability will be promoted.

Financing constraint mechanism

Financing constraints are the problem of capital shortage faced by enterprises in the process of development, and enterprises' innovation is especially vulnerable to the impact of financing constraints (Song et al., 2015). Therefore, the issue of financing constraints has attracted extensive attention from scholars at home and abroad since it was put forward. II mainly affects the financing constraints of enterprises in two aspects. On the one hand, II promotes the construction of financing platforms and the interaction of financing information (Keller, 2002), improves the financing environment of enterprises, enhances the resource allocation efficiency of financial elements and the opportunities for high-quality enterprises to obtain financing, and thus alleviates the financing constraints of enterprises. On the other hand, traditional banks often adopt physical mortgages and other ways to make loans, so it is difficult for enterprises with fewer assets but strong technological innovation ability to obtain financing, while the construction of II promotes more comprehensive market information, reduces the entry threshold of the credit market (Buchak et al., 2018), and thus alleviates the financing constraints of innovative enterprises. Consistent with general innovation, enterprise GTI is also considered to be high-risk, investment-oriented, and long-cycle activities, which are highly dependent on capital. As a result, it is challenging to meet the capital demand of enterprise GTI only by relying on internal financing. Therefore, if the financing constraints of enterprises are reduced, obtaining external funds will help enterprises reduce R&D risks and increase R&D investment, thus stimulating the innovation motivation of enterprises, increasing the success probability of GTI of enterprises, and thus promoting the green transformation development of enterprises. Based on the above discussion, this paper proposes the following:

Hypothesis 1: Information infrastructure construction can promote enterprises' green technological innovation, and it holds for both quantity and quality dimensions.

Hypothesis 2: Information infrastructure construction promotes enterprises' green technological innovation by promoting enterprises' digital transformation.

Hypothesis 3: Information infrastructure construction can promote enterprises' green technological innovation by easing corporate financing constraints.

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The influence of II construction on enterprise GTI may be influenced by regional heterogeneity and the life cycle of enterprises. The first is the regional heterogeneity. Chinese cities have apparent regional characteristics, which can be typically divided into regions with different carbon-reduction pressure. Among them, regions with high carbon-reduction pressure are relatively developed, and external conditions such as the market environment and intellectual property protection level are better, which are more conducive to II to play the driving effect of GTI. The second is the life cycle heterogeneity. The life cycle theory points out that the life cycle of enterprises can be divided into growth period, maturity period, and decline period (Adizes, 1989). Enterprises with different production cycles have different characteristics, and these characteristics may influence the extent to which enterprises accept II and thus affect the promotion effect of GTI. Among them, compared with the recession period, enterprises in the growth and maturity stages are more susceptible to the positive spillover effect brought by II construction (Wang et al., 2022). Therefore, based on the above discussion, this paper proposes:

Hypothesis 4: The promoting effect of information infrastructure construction on enterprises' green technological innovation will be affected by the regional heterogeneity, in which regions under high carbon-reduction pressure will benefit more.

Hypothesis 5: The promoting effect of information infrastructure construction on enterprises' green technological innovation is influenced by the life cycle of enterprises, in which enterprises in the growth and maturity stages gain more benefits.

Theoretical mechanism structure diagram and pre-trend tests

The theoretical mechanism employed in the study is portrayed in *Figure 1*.

The time trend chart can roughly judge the change trend between the treatment group and the control group samples before and after the implementation of the policy, which is the premise of conducting DID research. As shown in *Figure 2,* this article takes the promulgation of the Broadband China policy in 2014 as an example. After 2014, the patent application volume of pilot cities (treatment group) experienced a higher degree of growth compared to non-pilot cities (control group), and the gap between the two gradually widened. However, before 2014, the two had a relatively consistent trend of change.

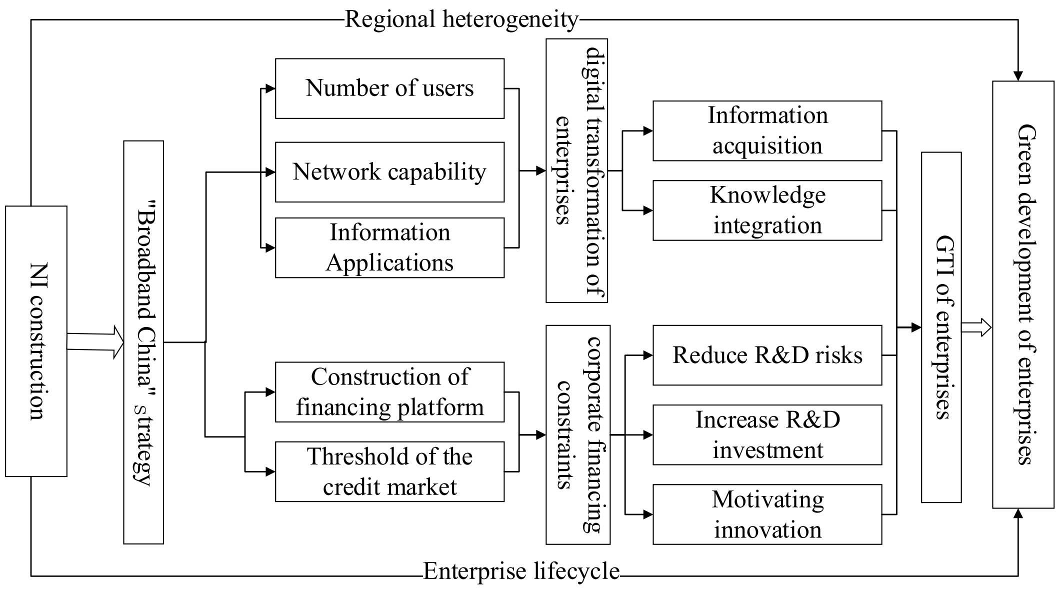

Figure 1. *Theoretical mechanism structure*

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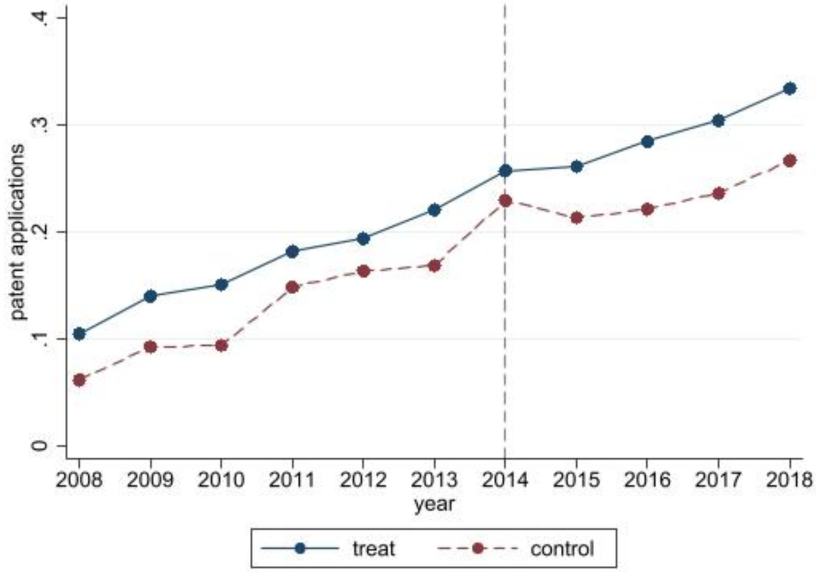

Figure 2. *Pre-trend tests result*

Materials and methods

Model setting

According to the implementation plan of the Broadband China strategy, the Ministry of Industry and Information Technology and the National Development and Reform Commission jointly launched three batches of Broadband China demonstration cities from 2014 to 2016. The inaugural cohort of pilot cities was formally designated in late 2014, comprising thirty-nine urban centers. This initial selection strategically encompassed all provincial-level municipalities, provincial capitals, and cities with independent budgetary status. Representative examples include Beijing, Shanghai, Tianjin, Guangzhou, Shenzhen, and Chengdu. These municipalities, characterized by their advanced economic development and robust pre-existing digital infrastructure, were entrusted with the mandate to pioneer the deployment of sophisticated broadband networks, thereby establishing exemplary models for nationwide emulation. Building upon empirical insights derived from the first phase, the Ministry of Industry and Information Technology announced the second cohort in July 2015, which exhibited a substantial expansion to eighty-one cities. This iteration demonstrated a deliberate strategic broadening of geographical scope, incorporating numerous prefecture-level cities possessing distinct regional characteristics—such as Langfang (Hebei), Wuxi (Jiangsu), Foshan (Guangdong), and Yantai (Shandong). This expansion was designed to facilitate a more granular assessment of the broadband strategy’s applicability across diverse urban typologies and scales. The terminal cohort, promulgated in October 2015, introduced an additional twenty-four cities and special administrative regions, culminating in a comprehensive national portfolio of 144 pilot locations. This final selection manifested a pronounced emphasis on regional equilibrium and developmental potential, systematically integrating strategic nodal cities from central, western, and northeastern regions—including Hulunbuir (Inner Mongolia), Ya’an (Sichuan), and Pu’er (Yunnan). This systematic, phased allocation underscores a policy commitment to achieving synergistic and equitable broadband development across China’s heterogeneous regional landscape.

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This progressive pilot policy provides favorable conditions for this paper to study the GTI effect of enterprises in the construction of new II. Therefore, this paper assigns a value of 1 to the policy dummy variable in the year after the approval of broadband pilot cities in China and 0 before the approval. The following progressive differential fixed effect model is constructed:

$$y_{it} = \alpha + \beta Policy_{it} + \theta Control_{it} + \gamma_t + \mu_i + \epsilon_{it} \quad \text{(Eq.1)}$$

where t represents the year, and i represents the micro-enterprise individual; y_{it} represents the technological innovation of enterprises, including the number of patent applications (apply) and the total number of invention patent applications (apply_i); $Policy_{it}$ is the policy dummy variable, enterprise i is 1 in the demonstration area in year t; otherwise it is 0; $Control_{it}$ represents a set of control variables; γ_t represents the year fixed effect, $\mu_i$represents the individual fixed effect, ϵ_{it}represents other interference items. In order to control potential sequence correlation and heteroscedasticity problems when estimating *Equation 1*, this paper adopts individual-level clustering robust standard error.

Further, the vital premise of using the differential method to evaluate the policies of broadband demonstration cities in China is that the explained variables satisfy the parallel trend hypothesis between the treatment group and the control group; that is, if there is no policy impact, the change trend of the explained variables in the two groups of samples is the same. In addition, after the implementation of the policy, with time, the dynamic effect of the policy has changed to some extent. Therefore, it is necessary to test the dynamic effects of the policies of broadband demonstration cities in China in order to investigate whether there is a time lag or attenuation effect of the policy effect. In this paper, the event study method is used to conduct parallel trend test and dynamic effect analysis, and the regression model is set as follows:

$$y_{it} = \alpha + \beta_1 policy_{it}^{-5} + \beta_2 policy_{it}^{-4} + \cdots + \beta_5 policy_{it} + \cdots + \beta_9 policy_{it}^{4} + \beta_{10} policy_{it}^{5} + \theta Control_{it} + \mu_{it} + \delta_{it} + \epsilon_{it} \quad \text{(Eq.2)}$$

In *Equation 2*, the explained variablesy_{it}include the total number of green patent applications and the total number of green invention patent applications in the baseline regression, $policy_{it}^{-j}$ represents the j year before enterprise i entered the demonstration zone; similarly, $policy_{it}^{j}$ represents the j year after enterprise i entered the demonstration zone.

Furthermore, as described in the theoretical analysis, this paper examines the digital transformation mechanism and financing constraint mechanism, respectively. In order to measure the degree of digital transformation (DT) of enterprises, by referring to the practice of Yuan et al. (2021), this paper constructs an index that reflects the degree of digitalization of listed enterprises in China in a more comprehensive way and measures the degree of digital transformation of enterprises through the statistical semantic expression of national policies related to the digital economy and the text analysis method of machine learning in Python. In order to measure the level of financing constraints (SA) faced by enterprises, the SA index is used to analyze the current situation of financing constraints of enterprises by referring to the articles of Hadlock and Pierce (2010) and Ju et al. (2013). The formula for calculating the SA index can be expressed as: -0.737 × Size + 0.043 × Size^2 – 0.04 × Age. Size indicates the pair value of the total assets of the enterprise, and Age indicates the age of the enterprise. The SA index is negative, and the larger the absolute value is, the more serious the financing constraint is. SA used in this paper is the result after taking the absolute value.

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This paper adopts the mediation effect model to test the mechanism, and the model design is as follows:

$$apply_{it} = \beta_1 Policy_{it} + \beta_2 control_{it} + \mu_{it} + \delta_{it} + \epsilon_{it} \quad \text{(Eq.3)}$$

$$M_{it} = \beta_1 Policy_{it} + \beta_2 control_{it} + \mu_{it} + \delta_{it} + \epsilon_{it} \quad \text{(Eq.4)}$$

$$apply_{it} = \beta_1 Policy_{it} + \beta_2 M_{it} + \beta_3 control_{it} + \mu_{it} + \delta_{it} + \epsilon_{it} \quad \text{(Eq.5)}$$

where M represents the intermediary variables DT and SA, control represents the control variable, and other variables are consistent with the benchmark regression formula. *Equation 3* is the first-stage regression model. *Equation 4* is the second-stage regression model. *Equation 5* is the third-stage regression model.

Data sources and study variables

The research data used in this paper are mainly from the database of listed companies, including firms listed on the Shanghai Stock Exchange and Shenzhen Stock Exchange from 2007 to 2021. In order to avoid the interference of abnormal samples, ST and PT samples, financial and insurance samples, and samples with missing main variables are eliminated, and 1% and 99% quartile tail processing are carried out for continuous variables (variable definitions and descriptive statistics are in *Table 1A*). Among them, the total amount of green patent applications and the total amount of green invention patent application data came from the CSMAR green patent database (https://data.csmar.com/), CNRDS database (https://www.cnrds.com/), and wind database (https://www.wind.com.cn/).

Explained variable

Existing studies mainly measure the quantity and quality of enterprises' GTI in the following two ways. One is to use the total amount of green patent authorization and the total amount of green invention patent authorization as indicators to measure the quantity and quality of patents, respectively. The other is to use the total number of green patent applications and the total number of green invention patent applications as indicators to measure the patent quantity and patent quality, respectively. However, the latest research points out that it usually takes one to two years for a patent to be applied and granted, so the patent application data is more stable, reliable, and timely than the grant amount (Li and Zheng, 2016). Therefore, this paper chooses the total number of green patent applications and the total number of green invention patent applications as indicators to measure the patent quantity and patent quality, respectively.

Explanatory variables

The core explanatory variable is the dummy variable policy of broadband China Model cities, which is assigned according to the list and time of three batches of Broadband China model cities jointly conducted by the Ministry of Industry and Information Technology and the National Development and Reform Commission from 2014 to 2016. The Broadband China strategy pilot is an essential part of promoting information infrastructure construction. Still, there may be specific differences in information infrastructure construction between regions, leading to biased policy effects. This article

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further uses per capita broadband access (PBA) and per capita telecommunications income (PTI) to measure the level of information infrastructure construction as a supplement to the Broadband China strategy pilot. (Variable definitions and descriptive statistics are in *Table 1B*).

Control variables

The selection of control variables mainly takes into account five aspects. First, we adopt enterprise age and the number of directors to measure enterprise scale. The second is corporate profitability, which ROA, the net profit rate of total assets, measures. Thirdly, this paper uses comprehensive leverage to describe the solvency of enterprises. Fourthly, this paper uses the net profit rate of fixed assets to measure the sustainable development ability of enterprises. Finally, the stock market performance of enterprises is further taken into account, and the growth rate of net assets per share is adopted in this paper to measure it. The details of the variables with their descriptive statistics are portrayed in *Table 1*.

Results and discussion

Baseline regression results

The baseline regression results are reported in *Table 2*. Columns (1) and (2) report the policy effects of the Broadband China strategy pilot on green technology innovation in enterprises under the mixed effect model. It is found that the policy coefficient is significantly positive, whether it is the total number of green patent applications or the number of green invention patent applications, indicating that the Broadband China strategy can significantly promote green technology innovation in enterprises. Columns (3) and (4) report the policy effects of the Broadband China strategy pilot on green technology innovation in enterprises under the fixed effects model. It is found that the policy coefficient is significantly positive, whether it is the total number of green patent applications or the number of green invention patent applications, indicating that the Broadband China strategy can significantly promote green technology innovation in enterprises. Columns (5)-(8) show the regression results obtained by using per capita broadband access and per capita telecommunications income as proxy variables for information infrastructure construction. It is shown that the coefficients of per capita broadband access and per capita telecommunications income are significantly positive for both the total number of green patent applications and the number of green invention patent applications, indicating that information infrastructure construction can significantly promote green technology innovation in enterprises. All estimated results indicate that whether using the Broadband China strategy pilot to study the green technology innovation effect of information infrastructure construction or using more specific broadband access and telecommunications revenue as proxy variables, information infrastructure construction has a significant positive impact on the total number of green patent applications and green invention patent applications. The construction of information infrastructure has significantly improved the quantity and quality of enterprise innovation, with the effect of improving quality and efficiency. More importantly, the construction of information infrastructure significantly increased the total number of green patent applications by 18.20% and the total number of green invention patent applications by 15.26%, thus confirming hypothesis 1.

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Table1. *Description statistics*

Panel A										
Variables	**Measures/data sources**	**All samples**			**Samples from demonstration cities**			**Samples from other cities**		
		N	**Mean**	**Standard deviation**	**N**	**Mean**	**Standard deviation**	**N**	**Mean**	**Standard deviation**
apply	ln(Total number of patent applications)/CSMAR green patent database	28948	0.4100	0.7978	19518	0.4340	0.8170	9430	0.3603	0.7543
apply_i	ln(Total number of invention patent applications)/CSMAR green patent database	28948	0.2740	0.6294	19518	0.2951	0.6500	9430	0.2305	0.5819
age	Enterprise age/Wind database	28948	3.1433	0.2291	19518	3.1445	0.2347	9430	3.1407	0.2170
ROA	Net profit rate on total assets(%)/Wind database	28948	0.0513	0.0394	19518	0.0512	0.0385	9430	0.0514	0.0411
broadside	Number of directors/Wind database	28948	8.7015	1.7428	19518	8.6690	1.7528	9430	8.7687	1.7200
CL	Comprehensive leverage(%)/Wind database	28948	0.0024	0.0029	19518	0.0023	0.0027	9430	0.0027	0.0033
GRFA	Net profit rate on fixed assets(%)/Wind database	28948	0.8595	2.1537	19518	0.9920	2.3361	9430	0.5854	1.6831
GNAPS	Net asset growth rate per share(%)/Wind database	28948	0.1123	0.4283	19518	0.1163	0.4404	9430	0.1042	0.4022

Panel B				
	Variable description	**N**	**Mean**	**Standard deviation**
PBA	Total broadband access / total population at the end of the year in the region (%, CNRDS database)	28948	3.1463	3.2096
PTI	Total telecommunications revenue / total population at the end of the year (%, CNRDS database)	28948	0.3317	0.5893

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Table 2. *Benchmark regression results*

	(1) apply	(2) apply_i	(3) apply	(4) apply_i	(5) apply	(6) apply_i	(7) apply	(8) apply_i
policy	0.2588^{***} (25.80)	0.2014^{***} (25.37)	0.1352^{***} (9.69)	0.1188^{***} (10.06)				
PBA					0.0116^{***} (4.40)	0.0095^{***} (4.36)		
PTI							0.0689^{***} (7.32)	0.0392^{***} (5.31)
age	-0.4094^{***} (-19.91)	-0.2672^{***} (-16.42)	6.8885^{***} (94.63)	15.9050^{***} (259.35)	7.2003^{***} (64.53)	16.1582^{***} (175.00)	7.2920^{***} (77.46)	16.1163^{***} (206.12)
ROA	0.5273^{***} (4.02)	0.4134^{***} (3.98)	-0.2854^{*} (-1.70)	-0.2901^{**} (-2.09)	-0.4907^{***} (-2.90)	-0.4719^{***} (-3.36)	-0.4934^{***} (-2.92)	-0.4799^{***} (-3.41)
BM	0.0216^{***} (8.05)	0.0187^{***} (8.82)	-0.0041 (-0.84)	-0.0035 (-0.84)	-0.0100^{**} (-2.06)	-0.0088^{**} (-2.10)	-0.0104^{**} (-2.15)	-0.0092^{**} (-2.20)
DCL	4.6069^{***} (2.65)	2.5842^{*} (1.88)	2.0953 (1.23)	0.4813 (0.34)	1.7118 (0.99)	0.1387 (0.10)	1.5960 (0.93)	0.0474 (0.03)
GRFA	-0.0108^{***} (-4.88)	-0.0038^{**} (-2.16)	-0.0040^{*} (-1.87)	-0.0022 (-1.22)	-0.0038^{*} (-1.78)	-0.0020 (-1.10)	-0.0030 (-1.43)	-0.0014 (-0.76)
GRNAPS	-0.0167 (-1.54)	-0.0172^{**} (-2.00)	-0.0280^{***} (-3.87)	-0.0266^{***} (-4.84)	-0.0327^{***} (-4.55)	-0.0309^{***} (-5.64)	-0.0382^{***} (-5.31)	-0.0346^{***} (-6.31)
_cons	1.3994^{***} (20.45)	0.8644^{***} (15.97)	-21.2343^{***} (-82.80)	-49.7085^{***} (-228.45)	-22.1437^{***} (-58.63)	-50.4398^{***} (-160.50)	-22.4145^{***} (-70.52)	-50.2870^{***} (-188.65)
Firm-FE	YES	YES	YES	YES	YES	YES	YES	YES
Year-FE	YES	YES	YES	YES	YES	YES	YES	YES
N	28948	28948	28948	28948	28948	28948	28948	28948
Adj. R^2	0.042	0.036	0.013	0.015	0.015	0.015	0.018	0.016

Parallel trend test result

As explained earlier, with the implementation of the policy, with time, the dynamic effect of the policy can be changed to some extent. Therefore, the study used the event study method to conduct a parallel trend test to test the dynamic effects of the policies of broadband demonstration cities in China in order to investigate whether there is a time lag or attenuation effect of the policy effect. *Figure 3* shows the test results of parallel trends. d_t represents the time node of t years before the implementation of the policy, it represents the time node of t years after the implementation of the policy, and current is the time node of the year of the implementation of the policy. The results showed that there was no significant difference between the treatment group and the control group before the implementation of the policy in the parallel trend test results of both the total number of green patent applications and the total number of green invention patent applications, so the parallel trend test requirements were basically met. At the same time, after the implementation of the policy, the treatment group and the control group showed a significant difference. The difference increased with time, indicating that the pilot policy of the Broadband China strategy has a sustained effect on the technological innovation of enterprises in the region, and the effect is enhanced year by year.

Robustness test result

The GTI effect of the pilot policy of the Broadband China strategy may be interfered with by random factors, sample selection factors, endogenous factors, etc. Therefore, the following four methods are adopted in this paper for the robustness test:

The study initially employed the placebo test by referring to the study of Li et al. (2016) and Cantoni et al. (2017). The results are shown in *Figure 4*. The random coefficient is basically on the left side of the actual value of 0.1820, indicating that the policy effect was significantly weakened in terms of significance and intensity of action after dual randomization, which indirectly confirmed the robustness of the original conclusion.

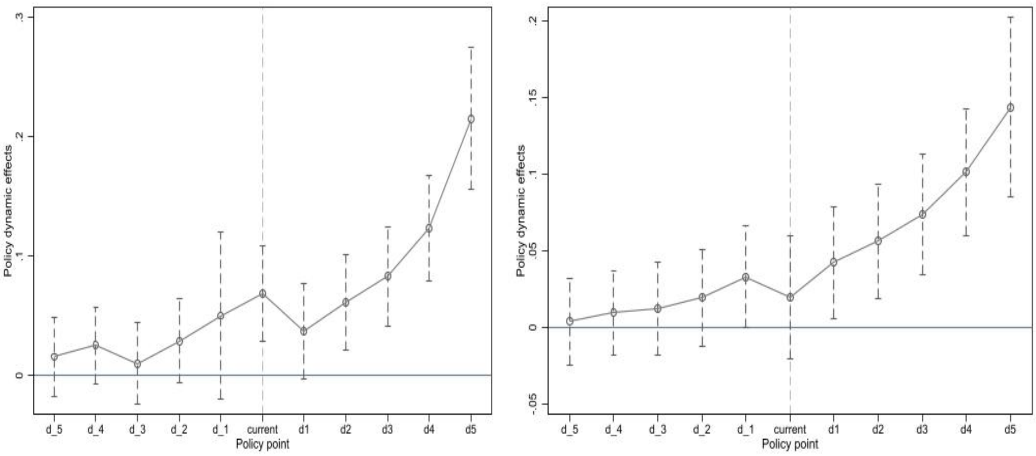

Figure 3. *Parallel trend test results: the left figure is the test result of total green patent applications, and the correct figure is the test result of total green invention patent applications*

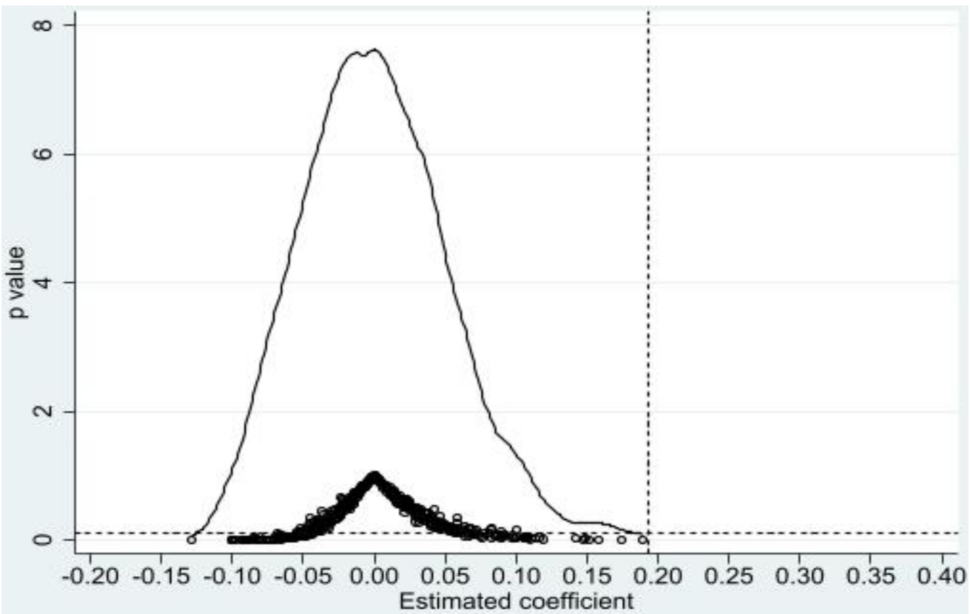

Figure 4. *Results of placebo test. The estimated coefficients from 1000 randomly assigned pilots are presented on the X-axis*

The study further employs the PSM-DID test, according to Dong and Zhu. (2016), a specific control group is selected for each treatment group through propensity score matching, which can alleviate the self-selection bias to a certain extent. The kernel density estimation chart shows that matching can correct the bias of control group selection, and the regression results are shown in columns (1) and (2) of *Table 3*: According to the

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weight, the matched samples in the control group were copied. No matter the total number of green patent applications or the total number of green invention patent applications, the results obtained by regression were consistent with the results above.

In addition, the study employed the instrumental variables following the study of Huang et al. (2019), the interaction term between the number of fixed telephones per 100 people in 1984 and the number of mobile Internet users in the previous year of each city is adopted as the instrumental variable of the pilot policy of the Broadband China strategy. The estimated results of the second stage are shown in columns (3) and (4) of *Table 3*: The results of the F-value and Wald-F statistic test in the first stage show that there is no weak instrumental variable. For both the total number of green patent applications and the total number of green invention patent applications, the estimated coefficient of the policy item is still significantly positive at the level of 1%, indicating that the benchmark conclusion of this paper is still valid after the endogenous problem is alleviated.

At last, the study eliminated part of the particular sample test. Compared with other cities, provincial capitals and municipalities directly under the Central government have certain particularities in resource allocation, history, and culture, which may influence the analysis results of the benchmark model. In this regard, this paper re-estimated the benchmark model after excluding the samples of provincial capitals and municipalities. The results are shown in columns (5) and (6) of *Table 3*. The results are consistent with the benchmark regression for the total number of green patent applications and the total number of green invention patent applications.

The results of the above series of robustness tests show that both for the total number of green patent applications and the total number of green invention patent applications, the estimated coefficients of the policy are significantly positive, indicating that the baseline conclusion of this paper is robust, that is, the pilot strategy of Broadband China can significantly improve the enterprises' innovation performance.

Table 3. *Robustness test results*

	PSM-DID		**IV**		**Partial sample**	
	apply	**apply_i**	**apply**	**Apply_i**	**apply**	**apply_i**
policy	0.1372***	0.1204***	0.3168***	0.3234***	0.1218***	0.1006***
	(7.8655)	(8.1904)	(3.4439)	(4.1026)	(5.1920)	(5.1530)
age	7.1355***	15.8495***	-0.3392***	-0.1910***	6.8719***	15.8557***
	(69.1306)	(187.3781)	(-5.9099)	(-4.2543)	(66.7860)	(190.3326)
ROA	-0.6850**	-0.5018**	0.3919	0.3996*	-0.3142	-0.2553
	(-2.4629)	(-2.1224)	(1.5414)	(1.8985)	(-1.4177)	(-1.4185)
BM	-0.0076	-0.0085	0.0300***	0.0284***	-0.0127*	-0.0130**
	(-0.9650)	(-1.3754)	(2.9427)	(3.2546)	(-1.7937)	(-2.2819)
DCL	0.6532	0.0631	0.2288***	0.1065	3.1818	0.9944
	(0.2456)	(0.0291)	(4.1116)	(0.9154)	(1.4173)	(0.5555)
GRFA	0.0002	0.0001	-0.0152***	-0.0092***	-0.0010	-0.0004
	(0.0591)	(0.0418)	(-5.3552)	(-4.0617)	(-0.3303)	(-0.1423)
GRNAPS	-0.0619***	-0.0492***	-0.0051*	-0.0037*	-0.0239**	-0.0238***
	(-4.1838)	(-4.2108)	(-1.9163)	(-1.7700)	(-2.4032)	(-3.2270)
Firm-FE	YES	YES	YES	YES	YES	YES
Year-FE	YES	YES	YES	YES	YES	YES
F-statistic			3544.64			
Wald-F			1486.24			
_cons	49905	49905	27930	27930	15361	15361
Adj. R^2	0.0100	0.0106	0.0315	0.0156	0.0184	0.0198

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Mechanism test results

The study found that the construction of II can promote the incremental improvement of enterprises' GTI and its transmission mechanism are also explored; the results are shown in *Table 4*. The results of the first stage are columns (1)-(2) of *Table 4,* the results of the second stage are columns (3) and (6) of *Table 4,* and the results of the third stage are columns (4)-(5) and (7)-(8) of *Table 4*. In order to test the quantity and quality of innovation, the total number of green patent applications and green invention patent applications are further distinguished.

Digital transformation mechanism results

In fact, enterprise digital transformation, as a practical path for enterprises to achieve business transformation, innovation, and growth, has become an essential support for enterprise transformation. The improvement of II provides the foundation and conditions for enterprises' digital transformation. At the same time, enterprises' digital transformation may further stimulate the innovation power of enterprises. In particular, faced with the practical constraints of green development, enterprises have more obvious needs to realize green development through GTI. Therefore, promoting the construction of II is a crucial step to promote enterprises' GTI and thus achieve green development. The test results of the digital transformation mechanism are shown in columns (3)-(5) of *Table 4*. Among them, the policy parameter in column (3) is significantly positive, indicating that the pilot strategy of Broadband China can significantly promote the enterprise's digital transformation. In contrast, the policy parameter in columns (4) and (5) is significantly positive. Still, the absolute value of the parameter is significantly less than the result of the first stage, and the DT parameter is also significantly positive, indicating the existence of an intermediary effect. Therefore, II construction can promote enterprises' GTI by promoting enterprises' digital transformation, which verifies hypothesis 2. The above results show that the digital transformation of enterprises promoted by II construction not only promotes the quantity and quality of green innovation but also improves the efficiency and quality of green innovation.

Financing constraint mechanism results

One of the reasons for corporate financing constraints is that the financial market is not perfect, and in reality, what is more important is the information asymmetry between enterprises and financial markets. Therefore, an essential basis for alleviating corporate financing constraints is the establishment and improvement of information channels. With the improvement of II and the establishment of more and more digital economy platforms, corporate information channels have been significantly broadened and extended, and corporate financing constraints have been alleviated to a certain extent. Therefore, in theory, further improving II and promoting the construction and improvement of enterprise information channels is a meaningful way to ease the financing constraints of enterprises. Corporate financing constraints are an essential aspect affecting corporate GTI. Therefore, theoretically, the pilot strategy of Broadband China can also promote the improvement of GTI by easing corporate financing constraints. The test results of the financing constraint mechanism are shown in columns (6)-(8) of *Table 4*. Among them, the significant negative policy parameter in column (6) indicates that the pilot strategy of Broadband China can significantly alleviate the financing constraints of enterprises. In contrast, the significant positive policy parameters in columns (7) and (8)

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and the absolute value of the parameter are significantly less than the results of the first stage. At the same time, the parameter of SA is also significantly negative, indicating the existence of an intermediary effect. Therefore, II construction can promote enterprise GTI by easing enterprise financing constraints, which verifies hypothesis 3. This indicates that the construction of II provides conditions for enterprises' GTI from the level of capital, thus improving the output of enterprises' green innovation. Meanwhile, the output of such innovation also shows the double improvement of quantity and quality.

Table 4. *Mechanism test results*

	First stage		DT			SA		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	apply	apply_i	DT	apply	apply_i	SA	apply	apply_i
policy	0.1352*** (9.6981)	0.1189*** (10.0917)	29.8765*** (21.4761)	0.1026*** (7.3675)	0.0841*** (7.1466)	-0.9793*** (-49.5894)	0.0444*** (3.1630)	0.0433*** (3.6937)
DT				0.0011*** (5.5161)	0.0012*** (6.5315)			
SA							-0.0928*** (-11.0168)	-0.0772*** (-10.9173)
Control	YES	YES	YES	YES	YES	YES	YES	YES
Firm-FE	YES	YES	YES	YES	YES	YES	YES	YES
Year-FE	YES	YES	YES	YES	YES	YES	YES	YES
N	28890	28890	28890	28890	28890	28890	28890	28890
Adj. R^2	0.0129	0.0151	0.1231	0.0177	0.0234	0.2813	0.0265	0.0293

Heterogeneity test results

As mentioned in the previous theoretical analysis, the influence of II construction on enterprises' GTI may be characterized by regional heterogeneity and life cycle heterogeneity. Therefore, this paper initially tests the heterogeneity based on regions, and the results are shown in *Table 5*. Using the China Carbon Accounting Database, this study categorizes cities into three distinct carbon pressure typologies: high-pressure (top 20% emissions), transitional (middle 60%), and low-pressure (bottom 20%). Overall, except for the region with low carbon-reduction pressure, the regression results of the samples show that the coefficients of policy are significantly positive. The reason is that high carbon-reduction pressure compels enterprises to increase eco-innovation investments for carbon mitigation, which verifies hypothesis 4.

Secondly, the existing research on enterprises' GTI usually ignores the potential difference in time dimension, and enterprises in different life cycles may have significantly different acceptance levels of II, which will affect the play of green innovation promotion effect of II construction. This paper uses the cash flow model method to divide the enterprise life cycle and further tests the impact of II construction on enterprise GTI. The results are shown in *Table 6*. On the whole, the policy coefficients in the three periods are significantly positive, which indicates that the green innovation promotion effect of the Broadband China strategy pilot has a complete life cycle. No matter the growth period, maturity period, or even decline period, the green development momentum can be obtained from the II construction, but there are differences in the degree. In detail, enterprises in the growth and maturity stages benefit more from the green enabling of II, while enterprises in the decline stage benefit less. The reason is that

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compared with enterprises in the decline stage, enterprises in the growth stage and mature stage are more willing to accept the transformation and upgrading subjectively and tend to make strategic decisions of transformation and upgrading. Therefore, the construction of II mainly stimulates GTI of enterprises in the growth stage and mature stage. This verifies hypothesis 5. Finally, from the perspective of quality and quantity of enterprise green innovation, II construction significantly promotes the incremental improvement of the quality of enterprise GTI for enterprises in each life cycle.

Table 5. *Regional heterogeneity test*

	Region with high carbon-reduction pressure		**Region with middle carbon-reduction pressure**		**Region with low carbon-reduction pressure**	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	apply	**apply_i**	**apply**	**apply_i**	**apply**	**apply_i**
policy	0.1349***	0.1149***	0.1736***	0.1698***	0.0586	0.0696*
	(6.2521)	(6.4102)	(4.4767)	(4.8335)	(0.9436)	(1.6624)
Control	YES	YES	YES	YES	YES	YES
Firm-FE	YES	YES	YES	YES	YES	YES
Year-FE	YES	YES	YES	YES	YES	YES
N	14905	14905	4858	4858	1160	1160
Adj. R^2	0.0110	0.0131	0.0191	0.0264	0.0142	0.0155

Table 6. *Heterogeneity test of the enterprise life cycle*

	Growth stage		**Maturity stage**		**Decline stage**	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	apply	**apply_i**	**apply**	**apply_i**	**apply**	**apply_i**
policy	0.1350***	0.1172***	0.1627***	0.1449***	0.0946***	0.0909***
	(6.8751)	(7.2433)	(6.8666)	(7.0248)	(3.2744)	(3.6724)
Control	YES	YES	YES	YES	YES	YES
Firm-FE	YES	YES	YES	YES	YES	YES
Year-FE	YES	YES	YES	YES	YES	YES
N	13899	13899	9584	9584	5437	5437
Adj. R^2	0.0164	0.0188	0.0173	0.0190	0.0072	0.0102

Conclusion and policy implications

Against the backdrop of the rapid development of the digital economy, the critical foundation for the green and high-quality development of China's economy has shifted from traditional infrastructure construction represented by railways to new infrastructure represented by information infrastructure construction. The green development mechanism of information infrastructure has theoretical and practical significance, so this article focuses on the perspective of green technology innovation and attempts to answer the driving effect of green technology innovation brought by information infrastructure. On the one hand, the digital transformation of industries such as energy, transportation, and finance is gradually deepening, and information infrastructure has become a long-term development demand. Especially in the face of the impact of the epidemic,

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information infrastructure is accelerating the evolution of the entire society towards digitization, networking, and intelligence. Human society is gradually entering a new era of perception, interconnection, and intelligence of all things. On the other hand, enterprises are facing new challenges in green transformation and upgrading, and there is an urgent need to use information infrastructure to assist enterprises in accelerating green technology innovation, breaking the shackles of green development, and promoting low-carbon and green social operations.

On the basis of reviewing relevant literature and theoretical analysis, this article utilizes the quasi-natural experiment of the Broadband China strategy pilot and uses data from listed companies. By employing the double difference model and fixed effects model, this study empirically tests the green development effect brought by information infrastructure construction. The research conclusion is as follows: Firstly, as an essential carrier of information infrastructure construction, the Broadband China strategy pilot can significantly promote the incremental improvement of green technology innovation in enterprises, and this effect has dynamic sustainability. Secondly, the pilot of the Broadband China strategy aims to promote the incremental improvement of green technology innovation in enterprises by promoting digital transformation and alleviating financing constraints. Thirdly, the pilot program of the Broadband China strategy has heterogeneity in promoting green technology innovation among enterprises at the regional and enterprise lifecycle levels, and its effectiveness is more evident for enterprises in the central and eastern regions and at growth and maturity stages.

The policy implications of the above conclusions are as follows: First, we should reconsider the top-level design of the green and low-carbon orientation of digital infrastructure and take the market mechanism as the core to promote the green development of new digital infrastructure. At present, the double carbon goal is still a severe challenge facing China. The critical way to achieve the double carbon goal is to realize green development with green innovation as the core. Therefore, it is necessary to orderly practice the green development concept of digital infrastructure and realize the coordinated development of green emission reduction and digital economy. Second, we should give full play to the superimposed effect of the double revolution of information technology and energy technology and take the green spillover effect brought by the construction of II as the starting point to promote the green and high-quality development of the real economy. The construction of digital infrastructure, especially the construction of II, brings about the upgrading and transformation process of industrial intelligence, networking, and information, which is not accomplished overnight. It needs to distinguish regional differences and enterprise characteristics, etc. Therefore, it is necessary to avoid seeking fast quantity and provide conditions and environment for the improvement of innovation quality and quantity. Third, we should promote the coordinated development of the digital economy and low-carbon economy with green digital infrastructure as the core. At present, digital technology has become an essential element of green development, and its potential needs to be further stimulated. Therefore, it is necessary to promote GTI with digital technology, speed up the construction of the system, and enhance the efficiency and quality of enterprises' green development with digital infrastructure.

Limitations and future research directions

This study has some limitations that need to be explored further in future studies. First, our research sample is limited to the data of listed companies in China; future studies can

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use different samples to verify the universality of the results, mainly focusing on whether the conclusions are applicable to small and medium-sized enterprises. Secondly, our research focuses on the promoting effect of green technology innovation on information infrastructure. However, from the perspective of explanatory variables, only the strategy of Broadband China is adopted as the research focus. The subsequent research needs to pay further attention to the promoting effect of green technology innovation on other information infrastructures. From the perspective of explained variables, our study only uses the green patent application as the representative variable of green technology innovation ability, and subsequent studies can use other indicators to expand this study. Finally, this paper only discusses the digital transformation mechanism and financing constraint mechanism, and other mechanisms can be analyzed in future studies.

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